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Accelerators as tools for discovery, innovation, and everyday life

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Particle accelerators

A particle accelerator is a scientific instrument that produces a directional stream of electrically charged particles, usually electrons or protons. The accelerator also boosts the energy of this beam and propels the particles to high speeds, close to the speed of light.

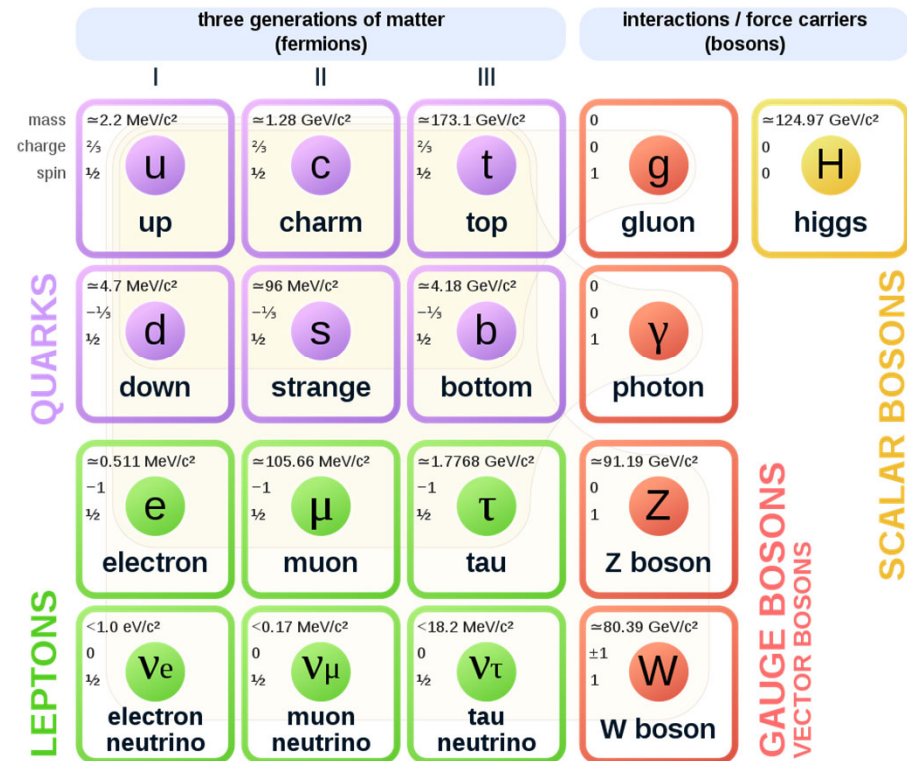


Elementary particles

In particle physics, an **elementary particle** or **fundamental particle** is a subatomic particle with no (currently known) substructure, i.e. it is not composed of other particles.

- Most known elementary particles: proton, neutron, electron, muon.
- Elementary Particle Physics allows us to address questions such as 'What is the world made of?' and 'What holds the world together?'

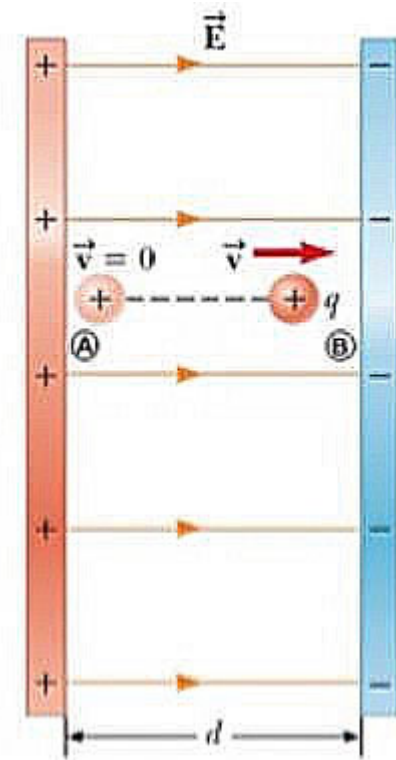
Standard Model of Elementary Particles



Principles of particle acceleration

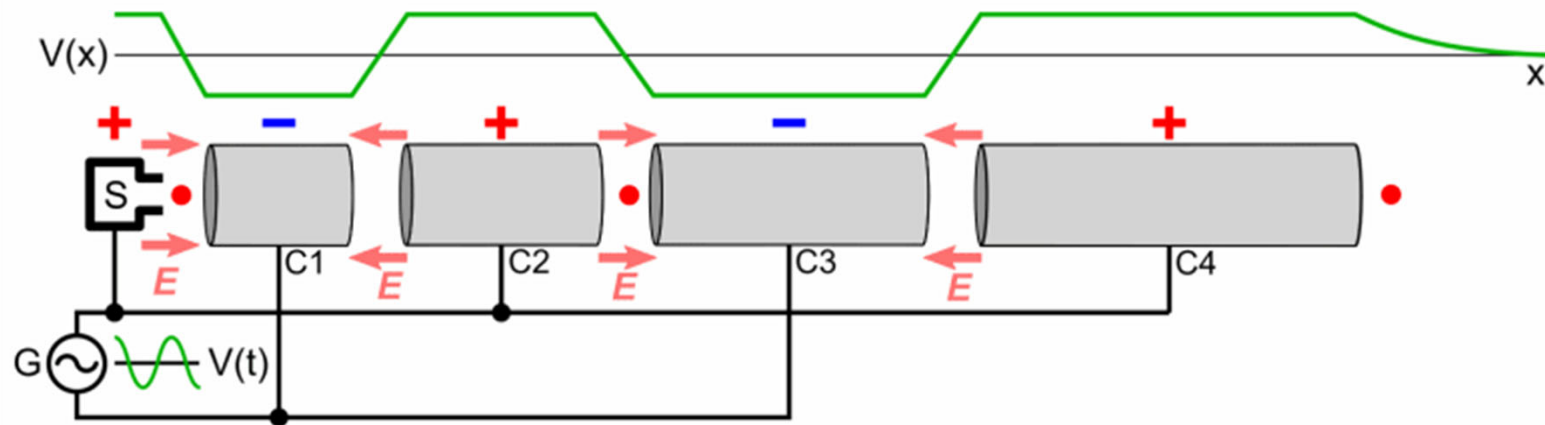
Particles are accelerated by either electrostatic or electromagnetic electric field E .

- The earliest particle accelerators used static electric fields.
- $\Delta W_{kin} = qEd$.
- Problems with electrostatic acceleration:
 - ✓ Gradient is limited.
 - ✓ Big electrostatic voltages are hard to produce.

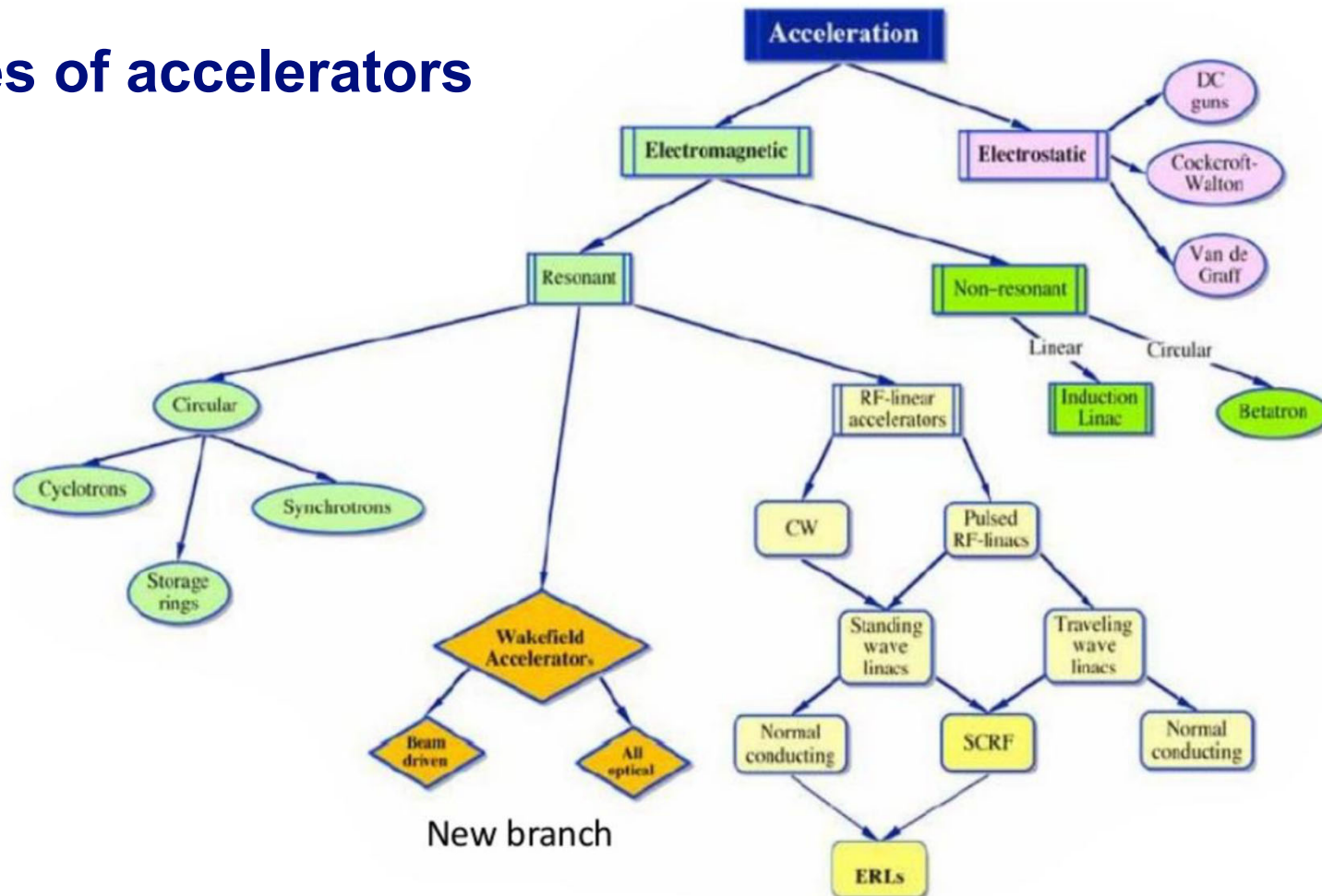


Particle acceleration in RF fields

Variable electromagnetic field is synchronized with the accelerating particle. The particle always sees the field in the correct accelerating phase.



Types of accelerators

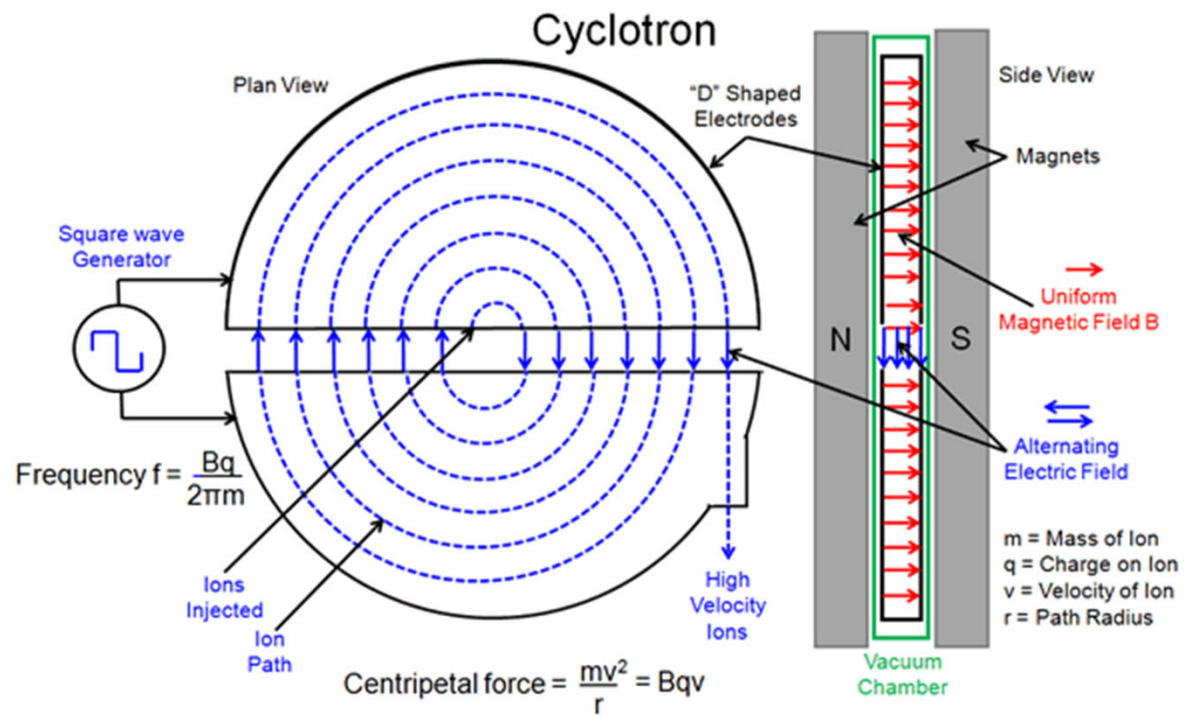


The first electromagnetic accelerator: a cyclotron

Nonrelativistic particles are kept on a circular path by a centripetal force provided by the magnetic field:

- $F = qvB$.
- Maximum achievable energy

$$W = \frac{q^2 B^2 R^2}{2m}.$$



Note that the accelerating field frequency is independent of the particle velocity and the path radius

The invention of particle accelerators

Lawrence's original cyclotron. Lawrence invented it in 1930 while working at University of California, Berkeley.



Nobel laureate Ernest Orlando Lawrence in 1939.



Accelerators grew up in size

Robert Wilson at the Fermilab Main Ring groundbreaking in 1969, for what became in 1972 the world's highest-energy proton accelerator.



Nobel laureate Hans Bethe and accelerator physicist Boyce McDaniel in 1968 in Cornell's half-mile-circumference accelerator tunnel.



An engineer checks electronics in the tunnel of the Large Hadron Collider.



Many technologies work together in accelerators

Magnets and vacuum chambers at Jefferson Laboratory. Visible here are a focusing magnet (red), a bending magnet (light blue) and the stainless steel vacuum chamber.



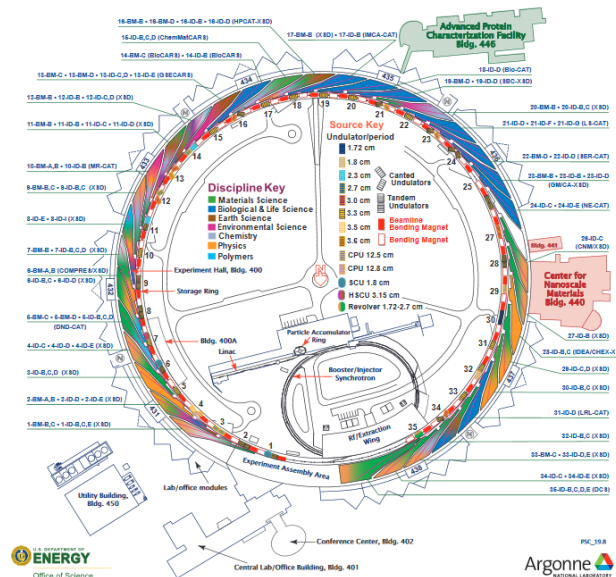
Accelerating structures. This structure operates superconductively, with almost no electrical resistance, by being cooled nearly to absolute zero. Superconducting operation saves enormously on the power bill.

Jefferson Laboratory accelerator control center. Modern accelerators are controlled by automated software that uses machine learning and optimization algorithms.



Modern day accelerator: APS

The **ADVANCED Photon Source**
at Argonne National Laboratory



Third generation light source

- US Department of Energy largest light source.
- Nominal electron beam energy 7 GeV.
- Circumference 1104 m.
- Revolution frequency 271.5 kHz.
- Photon energy 19.5 keV (hard X-rays).

Modern day accelerator: LCLS

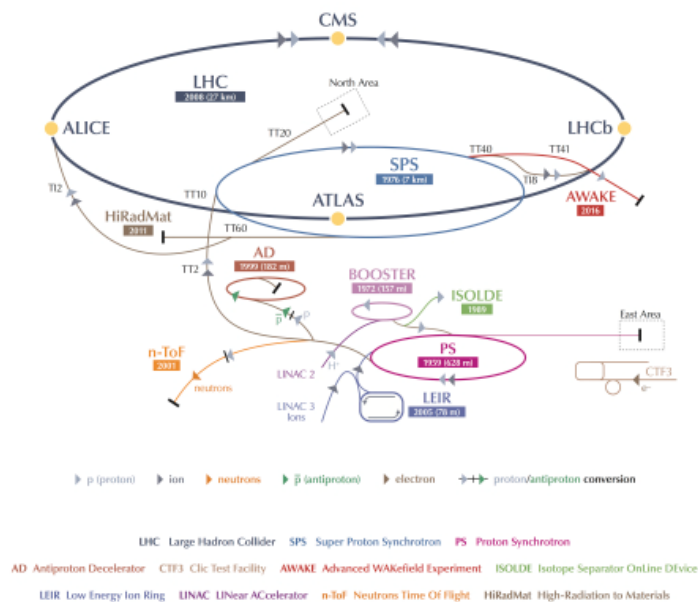


World's First Hard X-ray Free-electron Laser

- LCLS creates X-ray pulses a billion times brighter than previously available at synchrotrons.
- Nominal electron beam energy 3.5 GeV to 16.5 GeV.
- Accelerator length 1 km.
- Repetition rate 120 Hz.
- Photon energy 280 eV to 11.2 keV.

Modern day accelerator: LHC

CERN's Accelerator Complex



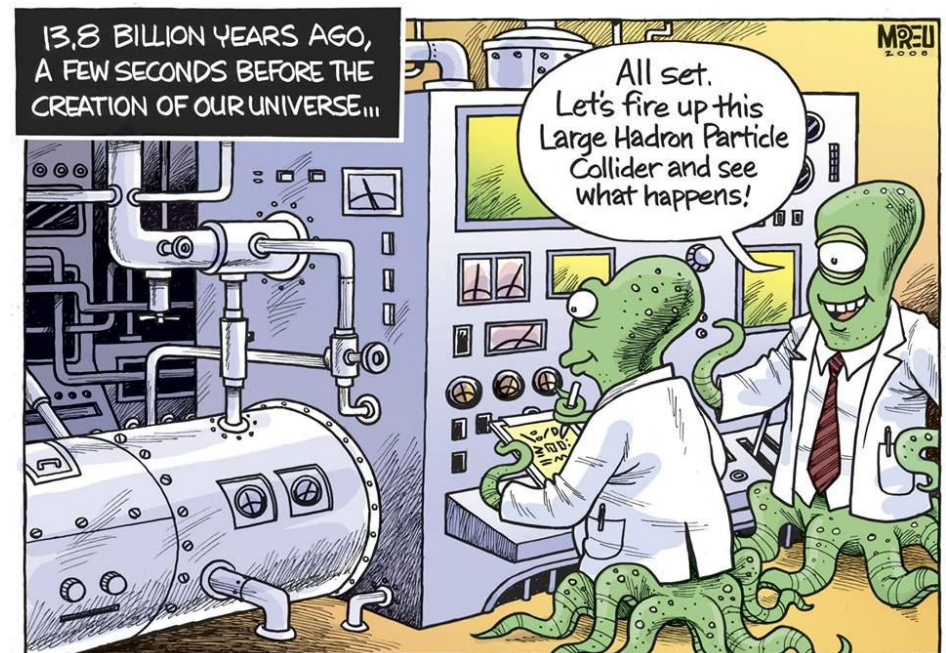
The Large Hardron Collider is the most powerful particle accelerator every built.

- The LHC is a particle accelerator that pushes protons or ions to near the speed of light and collides them to produce new particles and study high energy physics.
- Located in a tunnel 100 meters underground.
- Circumference 26659 m.
- Nominal proton energy 6.5 TeV.
- Nominal proton collision energy 13 TeV.
- Number of turns per second 11245.
- Number of proton collisions per second 1 billion.

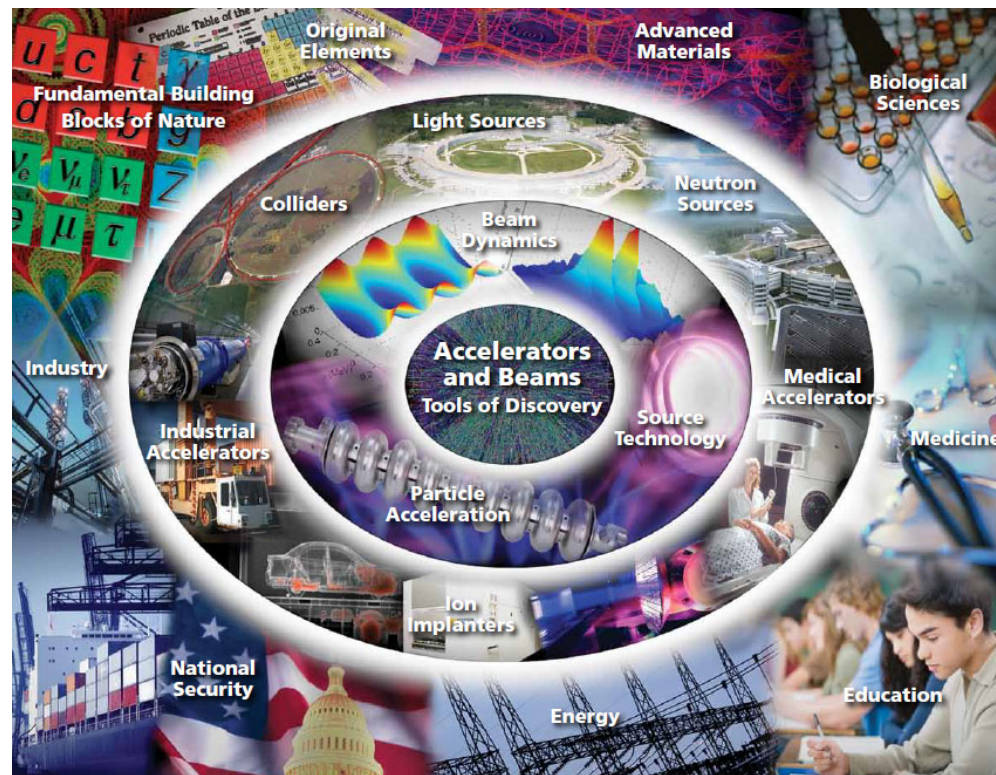


Is the Large Hardron Collider dangerous?

No. Although powerful for an accelerator, the energy reached in the LHC is modest by nature's standards. Cosmic rays collide with particles in the Earth's atmosphere at much greater energies than those of the LHC. These cosmic rays have been bombarding the Earth's atmosphere as well as other astronomical bodies since these bodies were formed, with no harmful consequences.

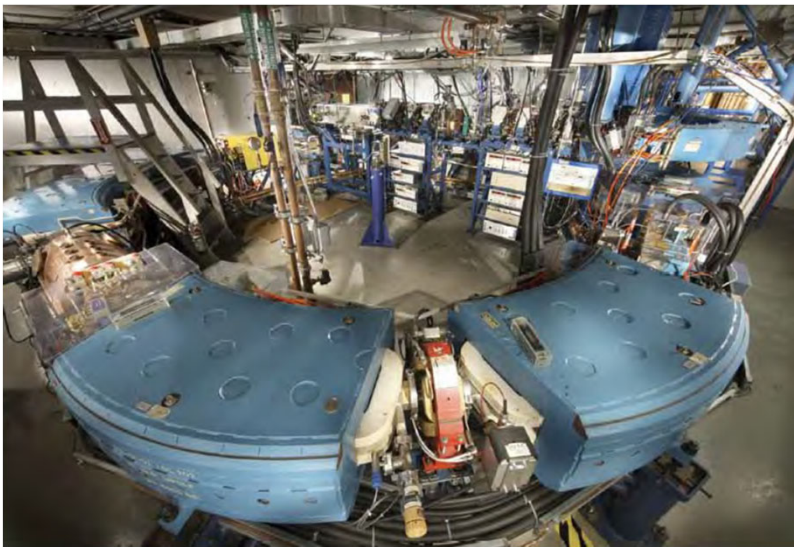


Accelerators, big and small



Accelerators for diagnosing illness and fighting cancer

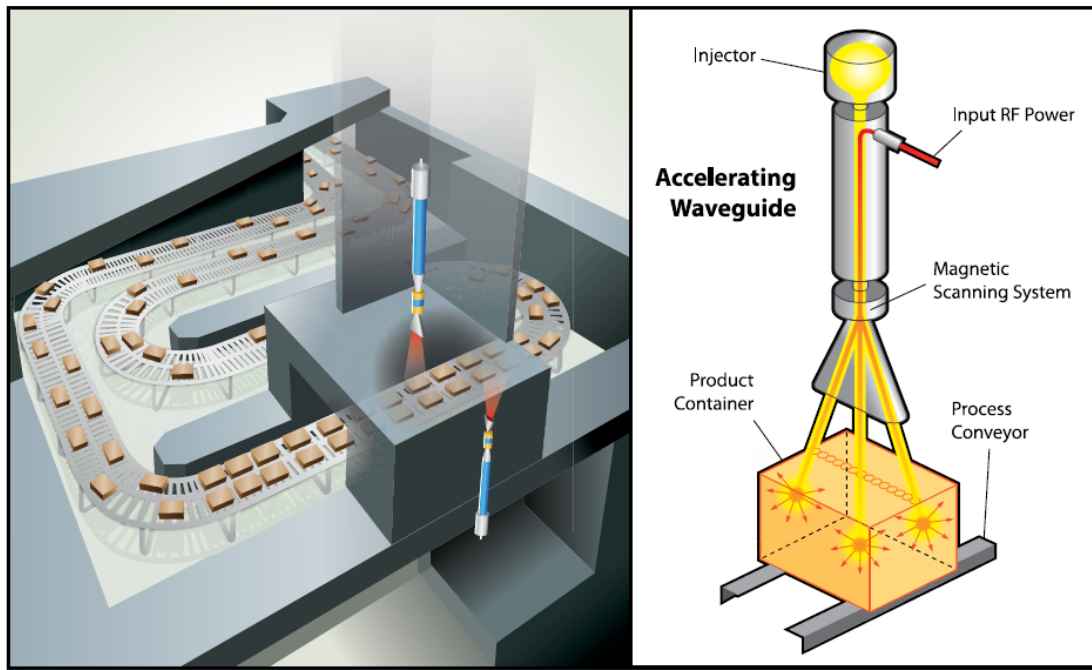
Hospitals and doctors use thousands of medical accelerators. Cyclotrons, modern versions of the original Lawrence invention, produce many different kinds of radioactive substances, called *isotopes*, for diagnostic procedures and therapy.



Many medical accelerators produce radiation for directly attacking cancer. Advances in proton and ion beam therapy are enabling doctors to avoid harming tissue near the cancer.



Accelerators to beat food-borne illness



Electron accelerators can make food much safer, just as pasteurization makes milk much safer. Electron beams, or X-rays derived from them, can kill dangerous bacteria like *E. coli*, salmonella and listeria.

Food irradiation is completely safe and does not degrade wholesomeness, nutritional value, quality or taste, consumer acceptance has been slow.

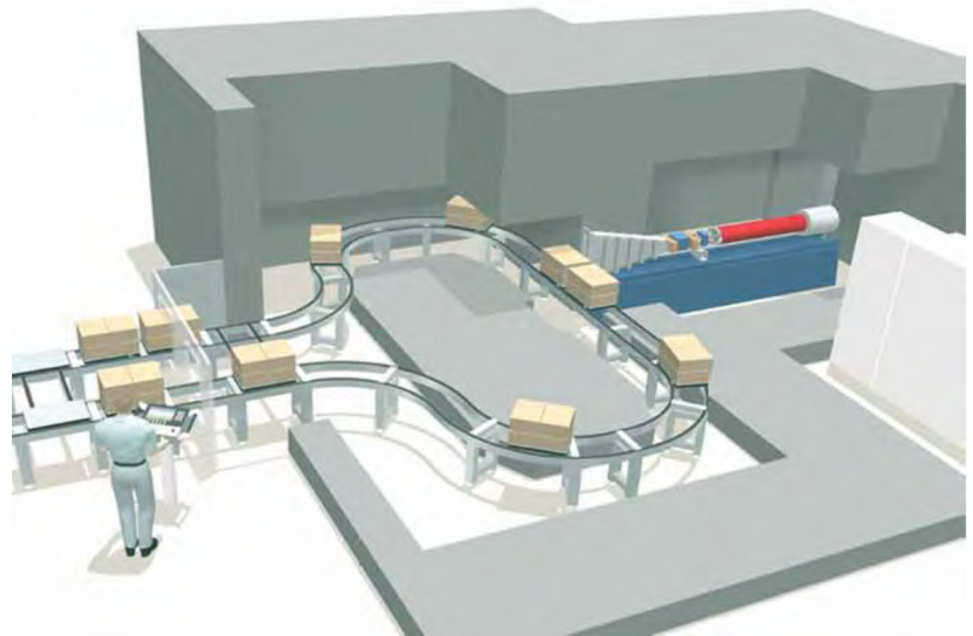
The international Radura symbol indicates food has been irradiated.



Accelerators make our band-aids safe

Electron beams can sterilize products effectively, efficiently, and fast. They kill all bacteria. They penetrate packaging, and even the shipping cartons holding the packages, so that there is no danger of contamination during or after sterilization.

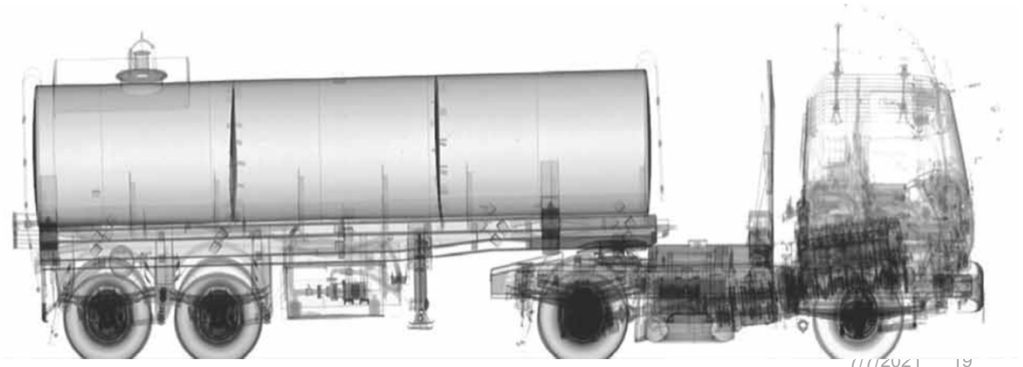
The “dose” from an electron beam with 10 to 50 kilowatts of power lets the conveyor run as fast as a few feet per minute, allowing sterilization of an entire truckload of boxes in only a few hours. A typical facility can process medical supplies so quickly that it needs several loading docks for offloading and reloading product.



Accelerators for cargo scanning

A single ship can bring up to 8000 tractor-trailer-sized cargo containers into an American port. Seven million containers arrive each year. Before distribution around the country, how can these large steel-walled boxes be inspected for what terrorists might have placed into one or some of them? Accelerators offer answers for scanning various kinds of cargo containers and vehicles effectively and efficiently.

The truck shown on the right carries a mobile 6 MeV X-ray imaging system for inspection of dense cargo.



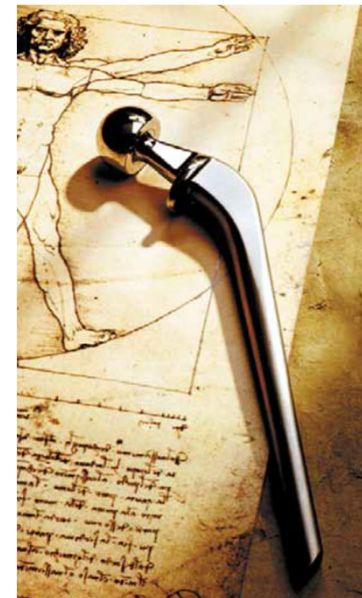
Accelerators for improving materials

An accelerator-based manufacturing technique called ion implantation modifies semiconductors' electrical properties precisely and cost-effectively, leading to better, cheaper electronics.

Ions are atoms with positive or negative charge. Implanting them very precisely in metal surfaces means greater toughness. In tools like drill bits, that means a longer working lifetime.

Ion implantation also means less corrosion. Greater toughness and less corrosion mean medical prostheses like artificial hips last longer.

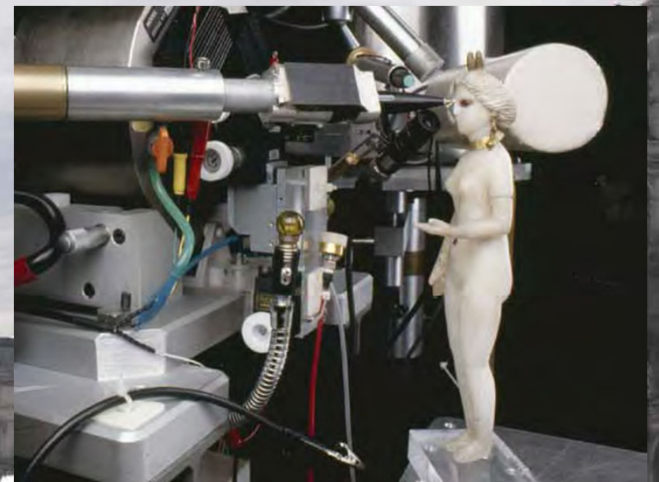
Nitrogen ions implanted into surgical alloys — as in this artificial femur — reduce wear and corrosion from body fluids, freeing patients from the need for repeated surgery.



Why does Louvre museum need an accelerator?

AGLAE, Accélérateur Grand Louvre d'Analyse Élémentaire in Paris, is the world's only accelerator facility fully dedicated to the study and investigation of works of art and archeological artifacts. It serves more than 1200 French museums. The 4-million-electronvolt proton beam delicately probes a large variety of materials: jewels, ceramics, glass, alloys, coins and statues, as well as paintings and drawings.

These investigations provide information on the sources of the materials, the ancient formulas used to produce them, and the optimal ways to preserve these treasures.



Accelerators and astronomy

Accelerators are like microscopes. Microscopes reveal what's extremely small. Accelerators reveal information about what's millions of times smaller still.

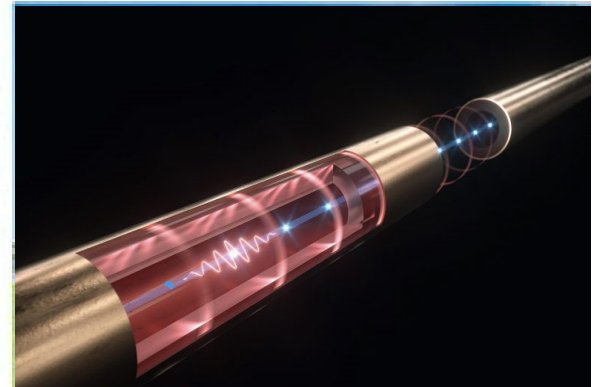
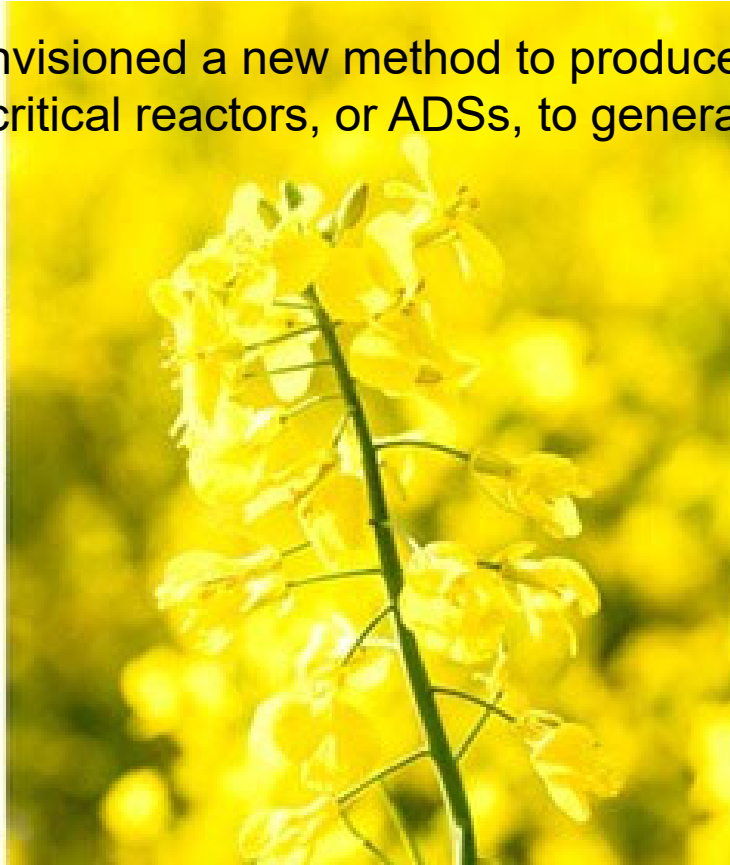
Accelerators are also like telescopes. Telescopes reveal the universe itself. Accelerators reveal information that helps astronomy. Accelerators are used to study nuclear processes that first occurred during the Big Bang and that continue in stars, novae and supernovae. This field is called **nuclear astrophysics**.

Accelerator physicists work with nuclear astrophysicists to use high-intensity, low-energy beams to explore reactions at stellar energies.



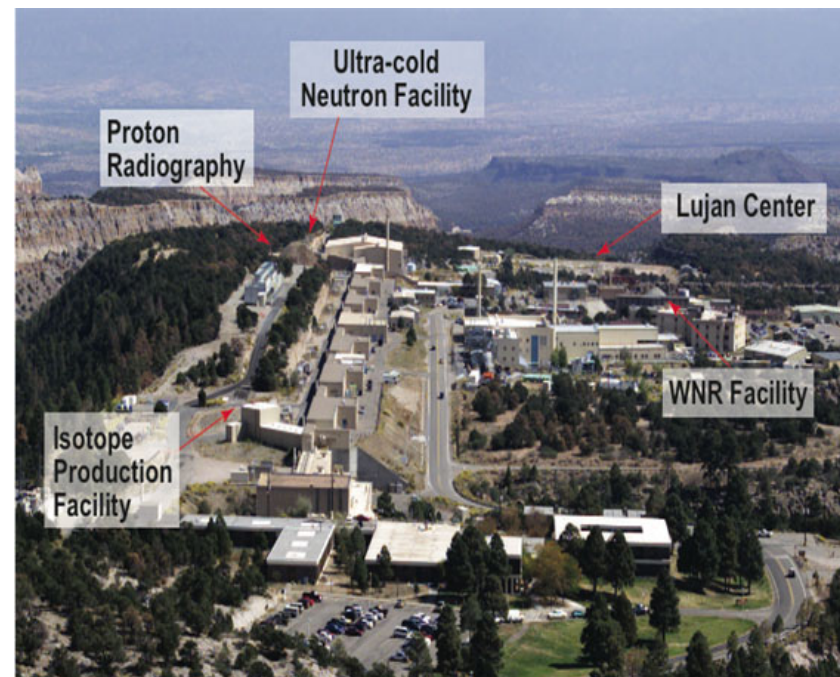
Could accelerators revolutionize nuclear energy?

Physicists have long envisioned a new method to produce nuclear power: accelerator-driven subcritical reactors, or ADSs, to generate electricity cleanly, safely, and cheaply.



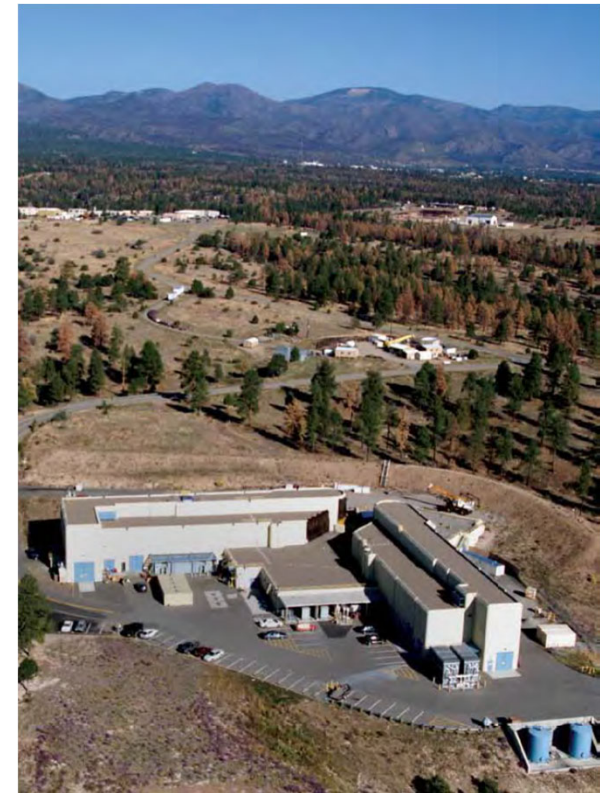
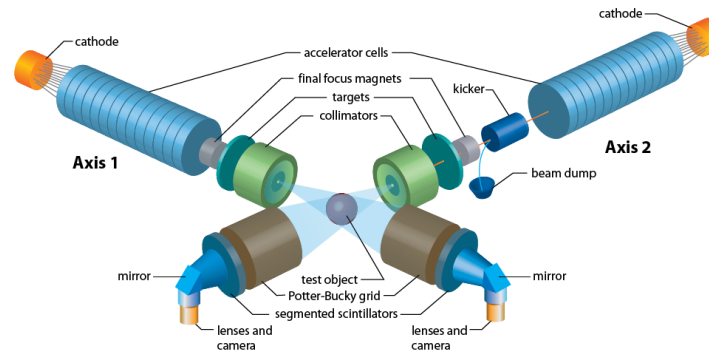
Accelerators at LANL: LANSCE

- The Los Alamos Neutron Science Center (LANSCE) is the major experimental science facility at LANL.
- LANSCE represents five experimental facilities that operate simultaneously.
- LANSCE contributes to the nuclear weapons program, nuclear medicine, materials science and nanotechnology, biomedical research, electronics testing, fundamental physics, and other areas.
- The heart of LANSCE is a 1-MW, 800-MeV proton accelerator that provides multiple proton beams for direct use, and also produces spallation neutrons used for a range of experimental activities.



Accelerators at LANL: DARHT

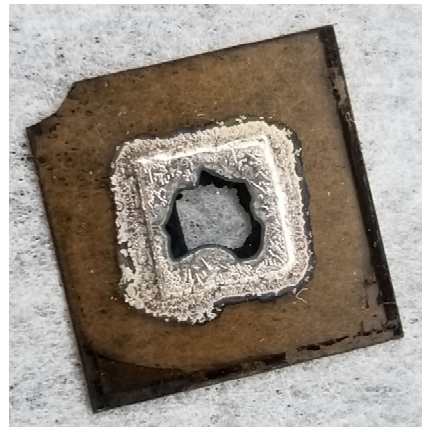
- In Dual-Axis Radiographic Hydrodynamic Test Facility, or DARHT Facility two electron accelerators at right angles to each other let scientists monitor realistic but non-nuclear tests of replacement components for the nation's nuclear weapons.
- Nuclear weapons testing moratoria preclude integrity tests. Therefore non-nuclear tests are necessary.
- In the test each electron beam is focused onto a metal target. This target converts the beam's kinetic energy into X-rays that generate images showing the dynamic events that trigger a nuclear detonation. Everything is real except the nuclear fuel.



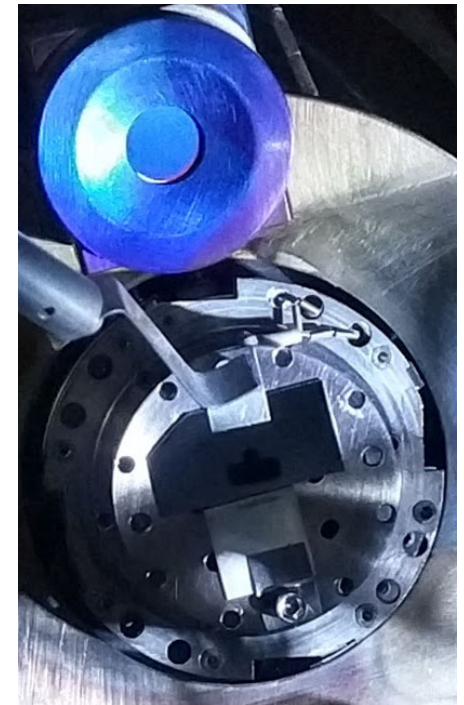
Accelerator research at LANL: cathodes

- Accelerators need particles – accelerator science builds sources
- Most materials DON'T want to release electrons
- Ultimate cathode should produce infinite current of mono-energetic, unidirectional particles
- No material is ideal, but some are better than others:
 - Diamond
 - Cs based semiconductors

**Single crystal
diamond
cathode**



**Growing CsTe
photocathode**



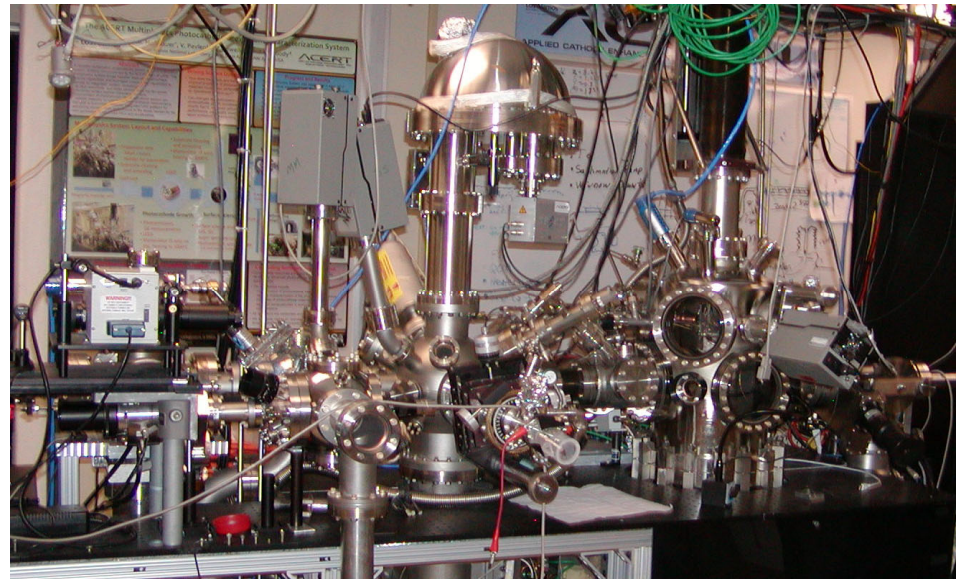
Accelerator research at LANL: cathode testing

- Testing cathodes is hard:
 - Samples require UHV
 - Cs is so reactive it will damage most characterization tools
- What do we test?
 - Material properties: Auger + XPS, ellipsometry
 - Beam properties: electron current, energy spread

**Beam
characterization
chamber**

**Materials
characterization
chamber**

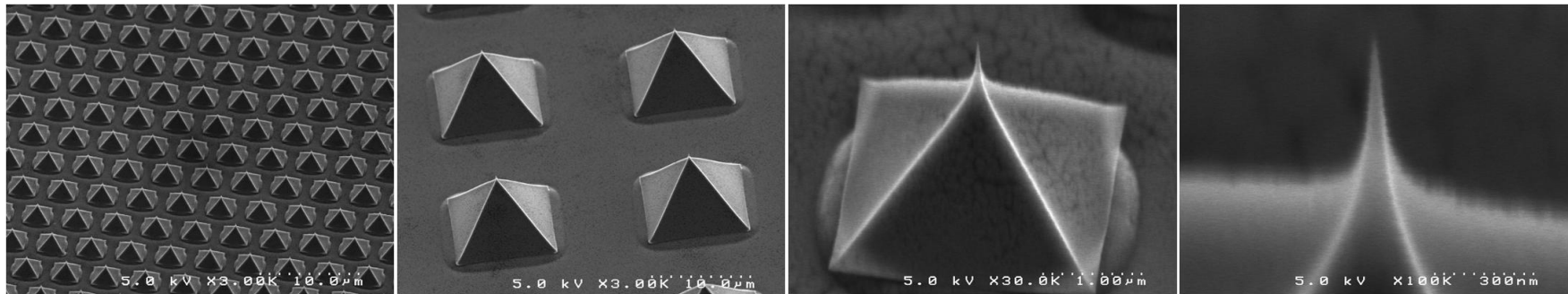
**Cathode
growth
chamber**



Accelerator research at LANL: diamond pyramid cathodes

Diamond field emitter arrays are arrays of diamond pyramids with exquisitely sharp tips.

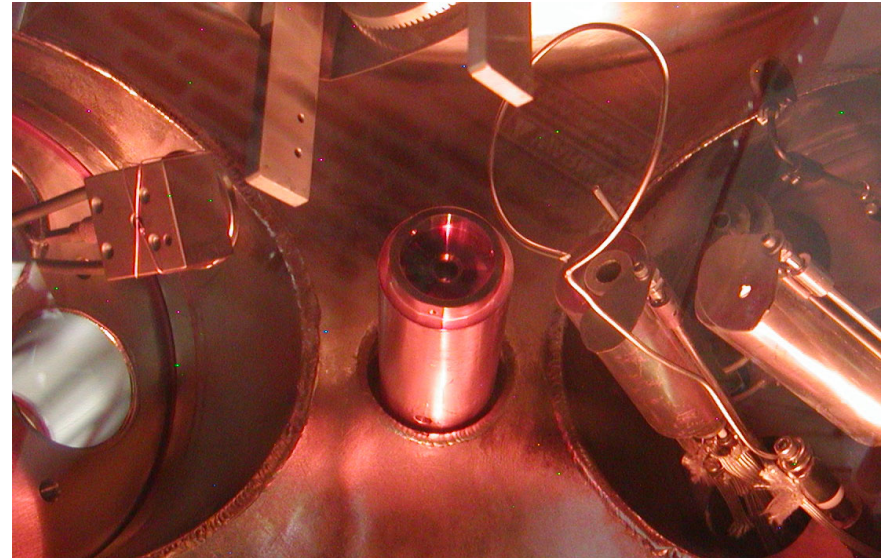
- Fabrication using standard silicon wafer technology allows a huge variety of array shapes
- Robust: DFEAs emit in poor or good vacuum and can be transported in air
- High thermal conductivity



Accelerator research at LANL: H- sources

- H- is the primary beam at LANSCE
- Works similarly to electron cathode
 - Similar materials
 - Electron transfers to hydrogen, NOT vacuum
- We combine an actual photocathode with hydrogen to make a better H- source

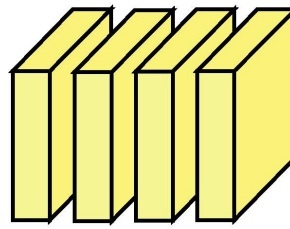
H- source chamber



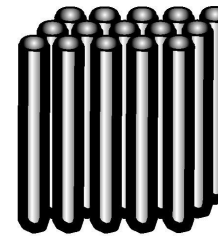
Accelerator research at LANL: photonic band gap structures

- Novel electromagnetic structures may allow for solving difficult electromagnetic problems such as suppressing higher order mode wakefields.
- LANL is a pioneer in photonic band gap structures for accelerators.
- Photonic band gap structures are frequency selective electromagnetic structures.

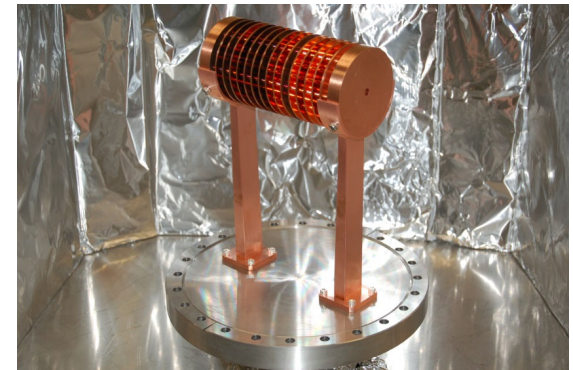
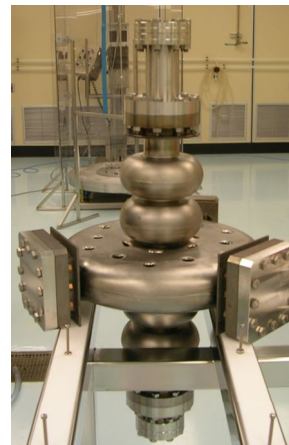
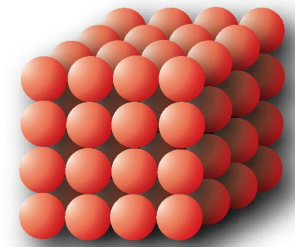
1D



2D

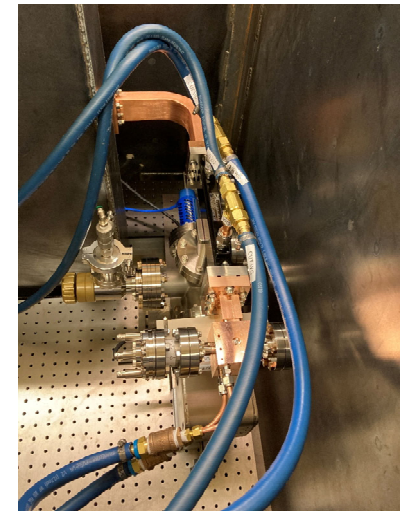
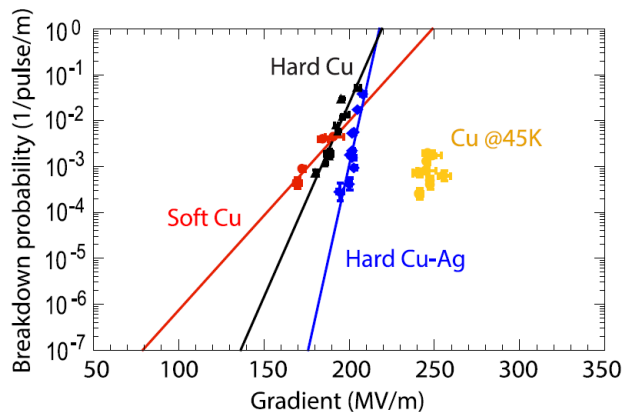


3D



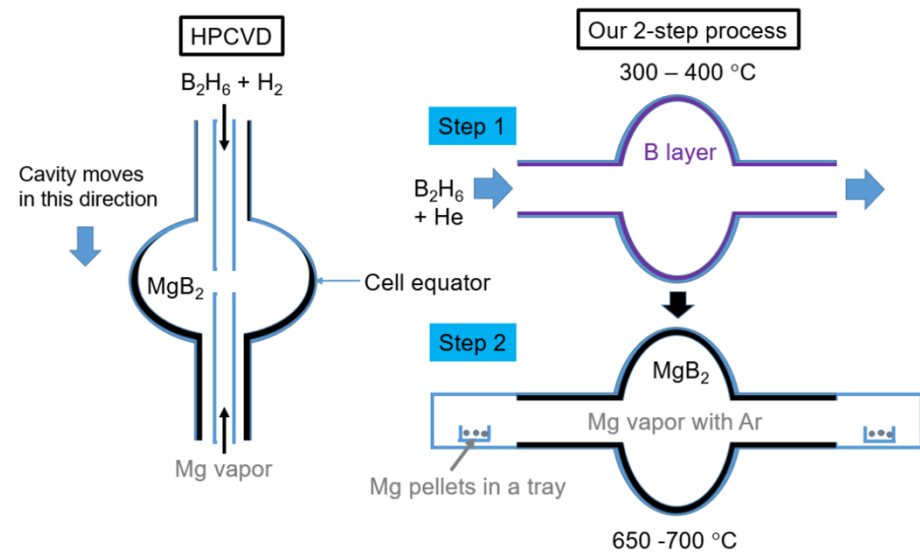
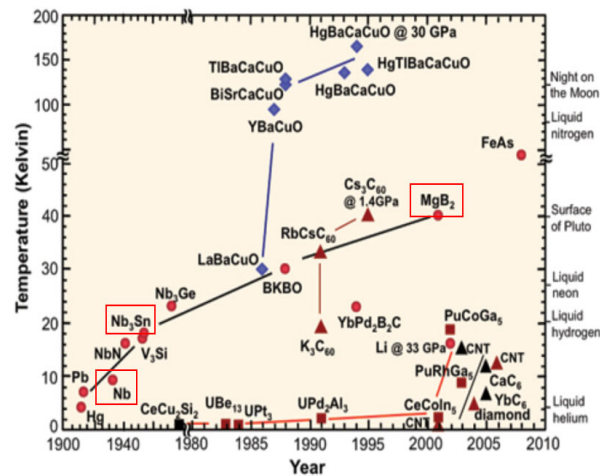
Accelerator research at LANL: very high gradients

- Accelerating gradient determines how much energy a particle gets over a given acceleration length.
- Accelerating gradient is limited by RF breakdown.
- Operating at high gradient allows for more compact accelerators.
- Reaching high gradients is a material science problem.



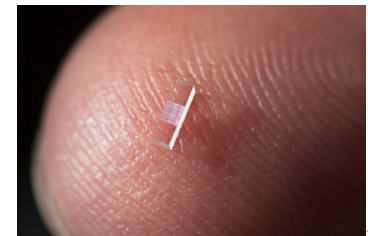
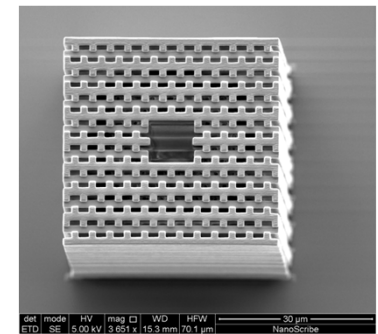
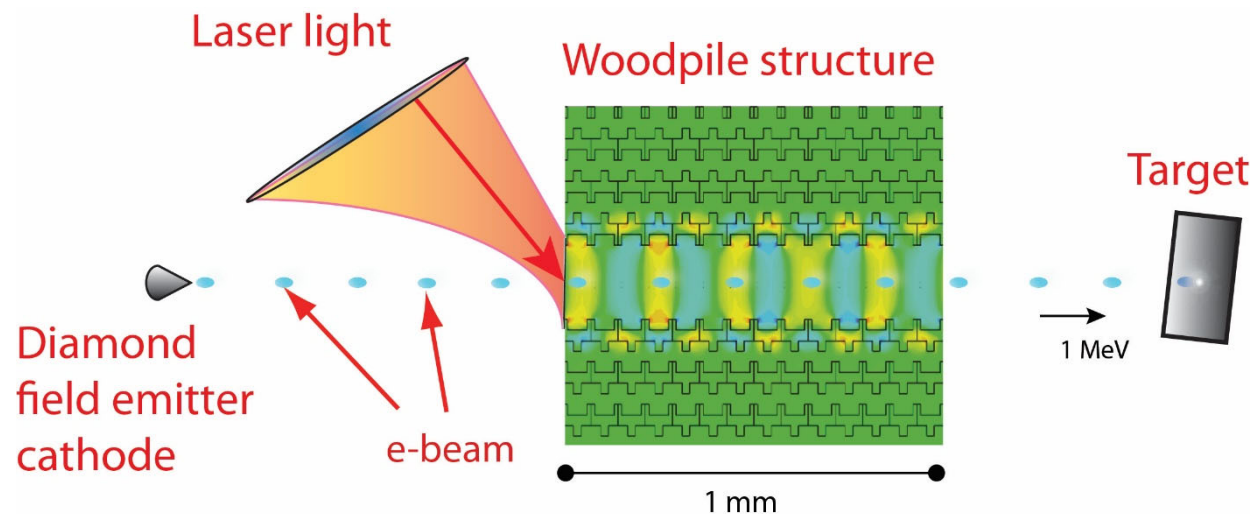
Accelerator research at LANL: superconducting structures

- Superconducting materials provide means to operate accelerating structures at high gradients with low losses.
- At LANL we study novel high temperature superconducting materials and ways to coat them on niobium cavities.



Accelerator research at LANL: dielectric laser accelerators

Diamond field emitter array cathodes and additive manufacturing technologies developed at LANL lead to practical demonstration of dielectric laser accelerators (DLAs).



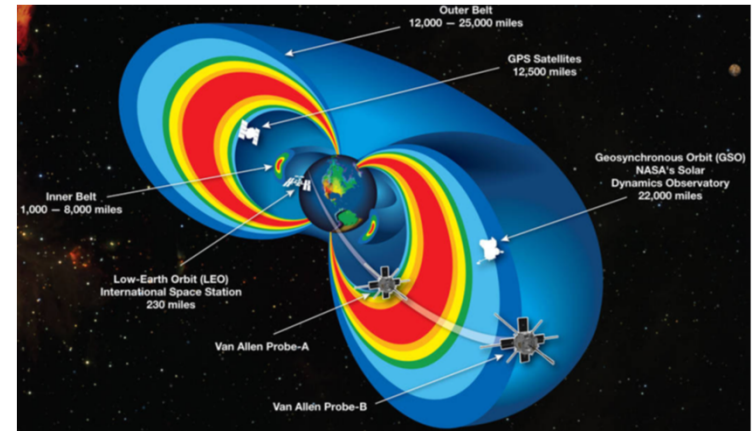
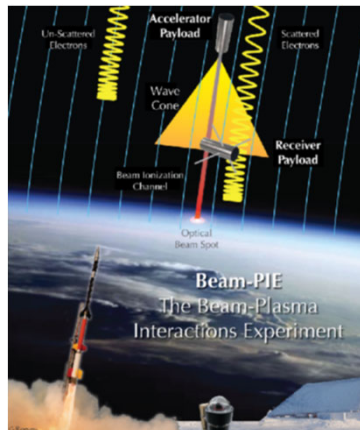
Accelerator research at LANL: infrared free-electron lasers

At LANL researchers developed high-power infrared FELs for defending ships from cruise missile attacks. The work was sponsored by the US Office of Naval Research. An onboard FEL's output wavelength can be changed to match varying atmospheric conditions. At the right wavelength, the laser beam can travel a long distance with the speed of light and deliver the necessary destructive power to counteract the speed-of-sound attack.



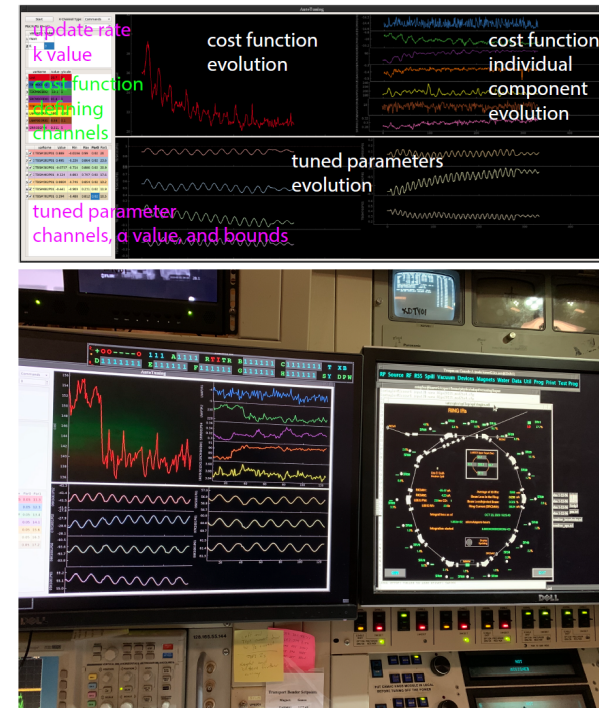
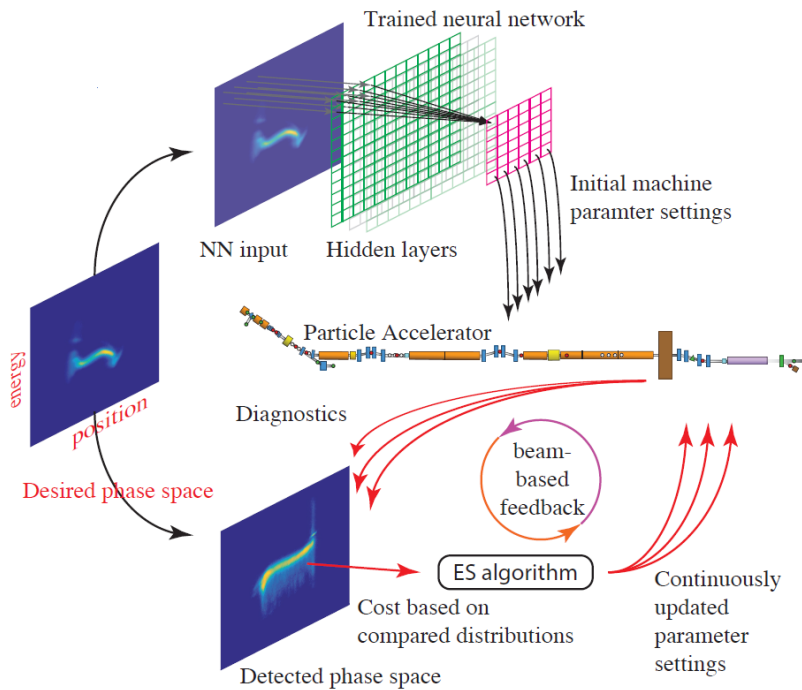
Accelerator research at LANL: accelerators-in-space

- Our world becomes more and more reliant on space technology orbiting the planet.
- One threat that could cripple satellite infrastructure is high energy electrons up to several MeV from solar wind or high altitude explosions that become trapped in the Earth's radiation belts.
- These electrons can cause electrostatic buildup and discharge on satellites causing critical damage. In today's world it can be catastrophic.
- At LANL we study ways to rapidly and harmlessly precipitate trapped electrons into the atmosphere.
- One approach is to generate electromagnetic waves with a modulated electron beam from an accelerator in orbit.



Accelerator research at LANL: machine learning

Accelerators operate with many thousands of input and output parameters. Machine learning is used to train an accelerator to operate in the desired state.



Education

Accelerators bring high-tech jobs. More than 30,000 accelerators worldwide serve an expanding variety of fields — and more than 65 manufacturers are shipping almost a thousand new systems each year. To design, build, operate and maintain these accelerators requires workers with an enormous variety of scientific, engineering, technological, medical and industrial skills. Accelerator physics and engineering graduates are in high demand in the United States and abroad.

